Electrostatic Radiator for Spacecraft Temperature Control

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Abstract. This paper describes development of and test results for an electrostatically switched radiator (ESR). This is a device that can control the radiation emitted from a surface by controlling the position of a thin membrane. The present structure has been fabricated for flight testing on NASA's ST5 New Millennium program. It consists of 4 separately controlled radiator sections with a total active area of 57.6 cm^2. As opposed to the original approach, this structure has the outer membrane at ground potential and is constructed onto a printed circuit board. In this paper we discuss the current state of development of the ESR, including device fabrication and test results.

THEORY OF OPERATION

The device, which has been described previously (Biter, Hess and Oh, 2003), is based on the use of a cover film that is attracted to the skin of the spacecraft via electrostatic forces. The key is the use of a thin compliant film that will establish good thermal contact under the small forces produced by electrostatic attraction. This membrane is fabricated with a high emissivity surface, so when it is in intimate contact with the spacecraft surface, it is close to the temperature of this surface and is emitting the energy associated with this temperature at the emissivity of the film. Alternately, when the system is in the "off" state, the film moves slightly away from the surface. This effectively changes the method of heat transfer from the spacecraft to the film from conduction to radiation, with the total radiated energy now limited by the energy radiated from the spacecraft surface. This surface can be fabricated to have a low emissivity so the total heat radiated from the spacecraft is small. The emissivity of the outer skin doesn't change, however its temperature drops and the result is a drop in the radiated energy due to the T^4 dependence of the radiative energy transfer. For the purposes of characterizing device performance, we can treat this as an effective emissivity. From theoretical calculations (Biter et al., 2002; 2003), it is potentially possible to switch the energy radiated from $\varepsilon \sim 0.95$ to $\varepsilon < .05$.

CURRENT STRUCTURE

The early designs for the ESR applied the electrostatic force by biasing the membrane. This resulted in the membrane being at high potential. For the ST5 spacecraft configuration, this requires application of a large DC voltage ~ 300V to operate the ESR. Since this membrane is located on the outer spacecraft skin, it was strongly desired to provide a design that shielded the outer membrane surface from these high voltages.

To address this concern, the system was redesigned to use a grounded membrane, with the high voltage applied to the center electrode. A schematic of the current ESR device incorporating this design is shown in Figure 1. The device is fabricated starting with a 0.010" thick two-sided printed circuit board (PCB). This board is metalized on both sides with hard gold and is adhesively bonded to the base with an electrically insulating adhesive. Although both the PCB and the adhesive layer result in a thermal resistance, the value is small enough so that it doesn't significantly affect the performance of the device. The membrane consists of a thin layer of polyimide metalized with aluminum followed by a spray deposited with a layer of high emissivity conductive paint (Aeroglaze Z307). The membrane that covers two active elements is attached to the PCB with six adhesive spacers; four at the corners and two at the middle. The electrical contact to the membrane also is made via a pressure contact from this active support strip. High voltage is applied to the center area which consists of electrodeposited gold which was selected for its low emissivity. The high voltage return is electrically isolated from chassis ground; however it is near ground potential. This return is connected to the membrane as well as to the bottom layer of the PCB which provides electrical shielding. This design shields the

DC fields and eliminates any potential hazard if the cover of the ESR is shorted. The only electrical change is an increase (approximately by 50%) in the capacitance, with the consequent small increase in power loss when switching.

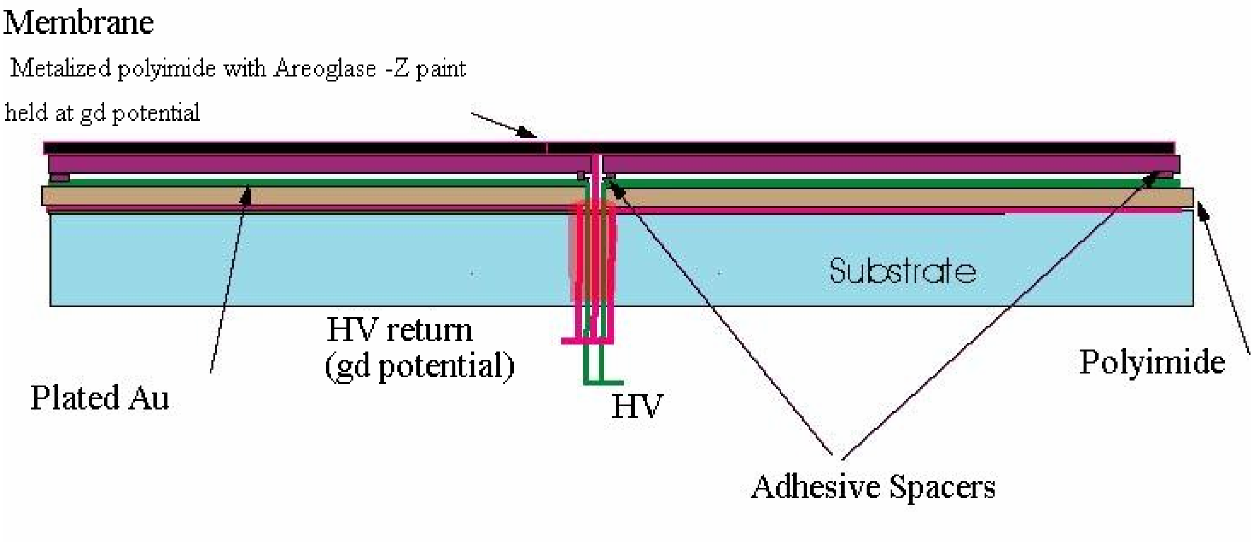


FIGURE 1. Schematic of Current ESR Structure Being Fabricated for ST5 Spacecraft.

ST5 MISSION

The ESR device can be use to control thermal radiation emitted from a surface and can be treated as a variable emittance device. It is currently one of the technologies to be tested on the ST5 constellation of satellites that are part of NASA’s New Millennium Program. This program is designed to validate several advanced technologies by obtaining multiple measurements in the harsh space environment. The ST-5 satellites are scheduled to fly as a secondary payload on a single expendable launch vehicle. Three satellites are planned to be deployed successively into a highly elliptical orbit with a final perigee altitude of at least 200 km and an apogee altitude of no higher than 38,000 km. The spacecraft will weigh approximately 25 kg with a planned mission lifetime of 3 months minimum, with a goal of 6 months. The current scheduled launch readiness date is December 2004.

Currently, two different variable emittance coating (VEC) technologies are planned to be flown with one device from each technology included on each of the three satellites (Douglas, 2001). These devices are to be mounted to an aluminum panel, which in turn, is mounted in a largely thermally isolated fashion to the spacecraft exterior top and bottom deck surfaces. The thermal isolation is sized to provide sufficient energy to measure VEC performance, but not enough to impact spacecraft performance in the event of a VEC failure. Performance of these devices will be measured by temperature data collected from thermistors mounted on the radiator assemblies. The data are collected both in the VEC electronics and recorded in the command data and handling system as a function of standard telemetry routines. The VEC control electronics, which are housed inside the spacecraft, apply the appropriate voltage to modulate the variable emittance devices. These technologies have demonstrated adequate performance in a laboratory environment. However, device longevity in the hard vacuum, radiation / atomic oxygen, contamination, thermal cycling, and micrometeoroid environment of space has not been demonstrated. In order to determine the effect of the space environment, the variable emittance coatings will be operated throughout the mission with testing planned over two complete orbits per week. Each individual validation run will last for at least 2 hours. Current mission specifications also require the technologies to be operated for no less than a total of 100 hours each. Both VEC technologies share the same footprint. Figure 2 shows the construction of the ESR device fabricated to fit this footprint. It consists of an aluminum substrate, measuring approximately 9 cm x 10 cm with 4 mounting tabs. In order to reduce extraneous effects, a 1 cm high sun shield surrounds the active film area. The sunshield is designed to block the sun from hitting the active surface of the ESR, based on a maximum sun angle of 5 degrees. There is a thermal insulator located at each of the mounting tabs, which is designed to produce a total conductance of approximately 0.1 W/K. Also visible in this photograph is the gold surface of the printed circuit board. This serves as the mounting surface for the ESR and also provides isolation for the ground plane. The gold surface is also the active electrode for the applied high voltage.

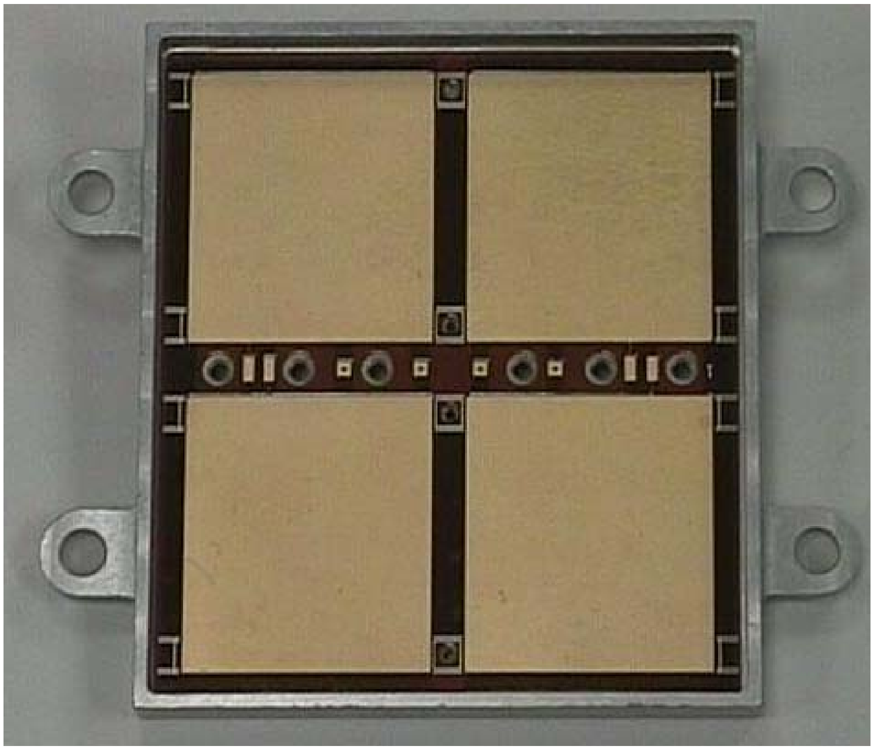
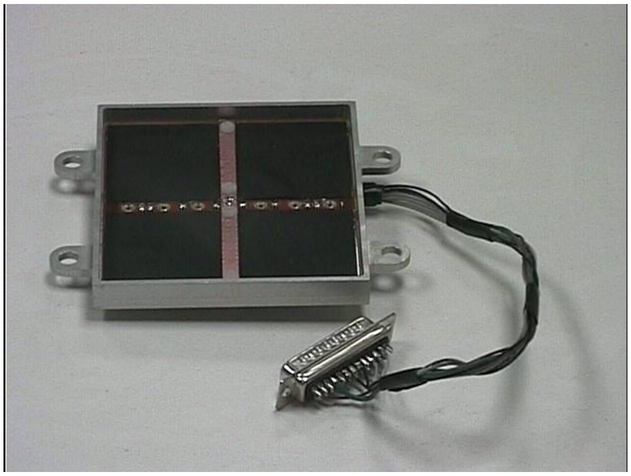


FIGURE 2. Picture of ESR Structure.

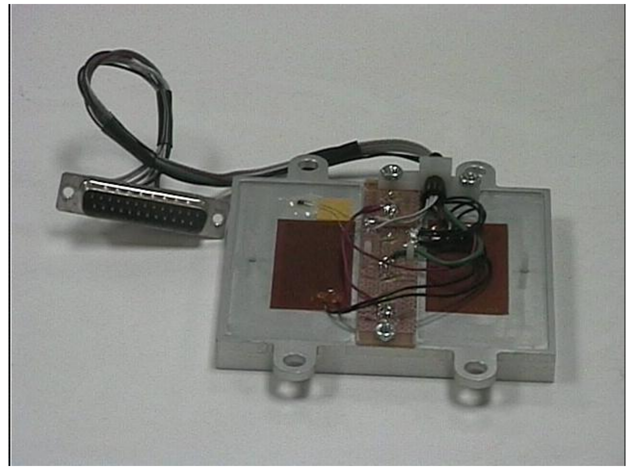
An assembled ESR with the radiator film sections attached is shown in Figure 3a. There are four segments which can be individually switched. Each segment measures 4.0 cm x 3.6 cm for an area per segment of 14.4 cm^2 and a total area of 57.6 cm^2 when all segments are switched. Thus, approximately 64% of the device surface area is switchable. The connection from the spacecraft to the ESR is from the back of the structure with the 4 voltage leads and two returns routed to the front of the structure via 6 feedthroughs. These feedthroughs are ceramic insulators screwed into the aluminum base and wired to pads on the printed circuit board. The membrane is fabricated in two sections and is electrically connected to the returns via the mounting strip visible in the center of the picture. Figure 3b shows the backside of the ESR test structure. There are 2 heaters mounted onto the back side of the aluminum substrate and 4 thermistors for testing. Two of the thermistors are dedicated for spacecraft use and the remaining two are used by the ESR control electronics. The heaters allow calibration of the conductance between the spacecraft and the ESR during spacecraft ground integration and testing so that the performance can be accurately determined. The electrical connection to the ESR structure is via a harness to the back of the structure, where it connects to a back PCB to connect with the feedthroughs, heaters and thermistors.

TESTING

Heat flow between the membrane and the substrate requires a vacuum for the ESR to operate, so it was necessary to construct a test system that fits these requirements before the device can be tested. Thus, testing is performed under space-like conditions. We have previously reported on a test system (Biter, 2002) shown below in Figure 4. This test system had a cold shroud that surrounds the ESR which is mounted horizontally face down. There was some concern that the “off” state would be affected by gravity, pulling the membrane away from the base. To address this issue, the system was redesigned so the test sample faces up. With this setup, any effect from gravity would be to increase the value of the "off" or low emissivity state and also increase the "high value". Testing performed under these conditions indicated no measurable effect. Figure 5 provides two different views of the test system.



(a) Front.



(b) Back.

FIGURE 3. Picture Of ESR.

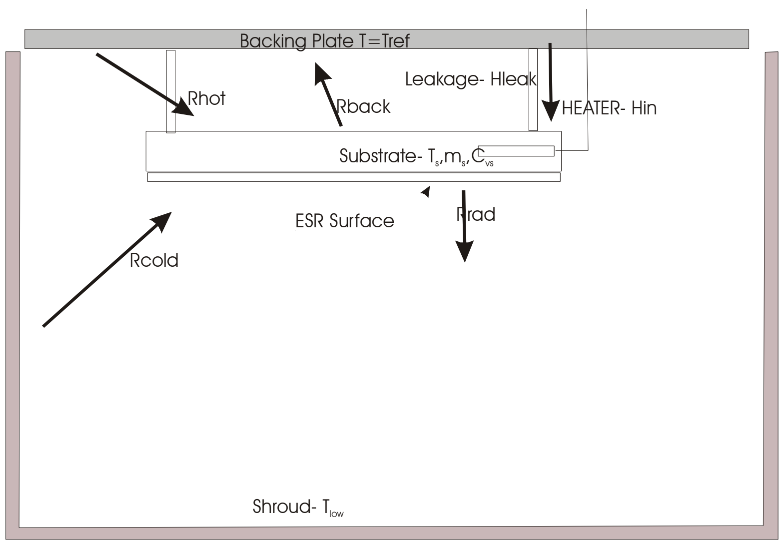
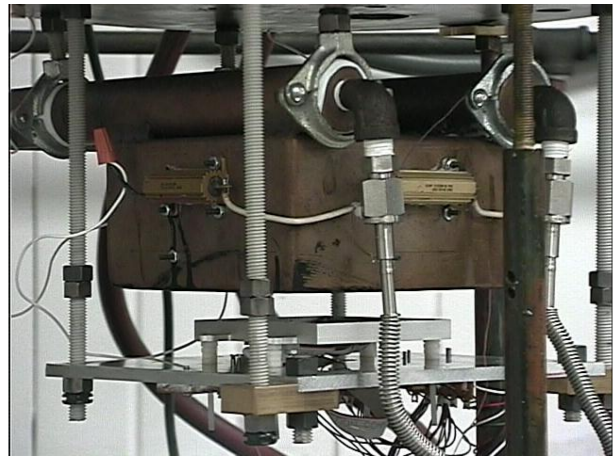


FIGURE 4. Schematic of Original Vacuum Test System.

For the measurements, the test specimen is placed on a temperature-controlled plate and the heat loss is measured by measuring the power required to maintain a set temperature, typically 24 °C. Although the heat loss with switching can give an accurate measure of the change in emissivity, stray losses (radiation from the back, un-switched areas, stray wires, leads, etc.), require a calibrated sample to obtain emissivity values. For calibration, the ESR structure shown in Figure 2 (i.e. without a cover film attached) was used. This exposes the low emissivity gold film. This produced a power reading of 3.71 watts, which is considered a "zero" reading. This gold area was then spray painted with a commercial black paint. This paint had an emissivity of ~ .84 as measured with an independent emissivity meter (Model AE Emissivity Sensor, DTS Inc., Dallas, TX). Measurement in the thermal vacuum test chamber produces a "black" reading of 5.56 watts. The area of the switched film was 57.6 cm^2 and the substrate temperature was 24 °C. The measured change in input power to maintain constant substrate temperature corresponds to a change in radiated power equivalent to $\Delta\varepsilon$ of 0.72. Assuming the gold surface had an emissivity ~ .04, the expected change in emissivity should have been about .80. Based on these results, our measurements on the change in emissivity are about 10% below the expected value. This error is suspected to result from the combination of the background (shroud) not being a true blackbody combined with a relatively large uncharacterized fraction of the surface which "sees" the shroud. The shroud is painted with a flat black paint but doesn't contain any baffles and a reflection from the shroud of ~ 3 - 4 % could account for this error. However, since the data provide conservative performance estimates, no corrections are being made at this time to account for these errors.

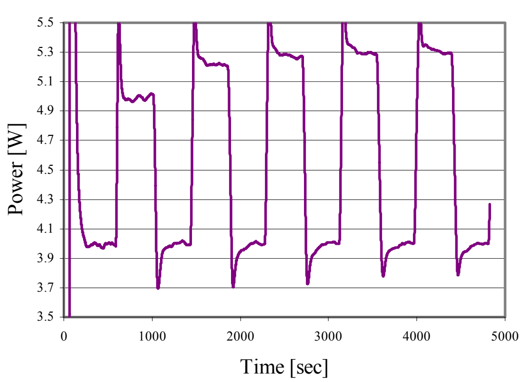
(a) Test System.



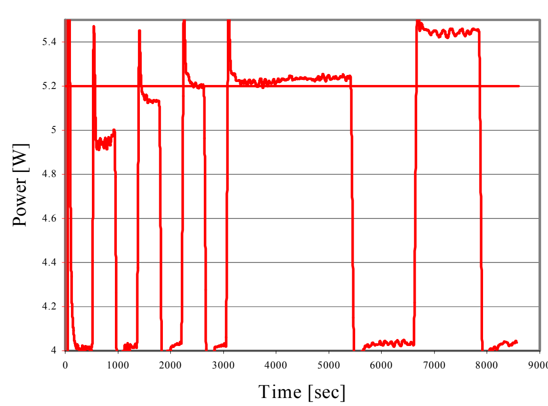
(b) Cold Shroud Close-up Showing ESR.

FIGURE 5. Picture of Current Vacuum Test System. The ESR is Visible in the Lower Portion of the Right Hand Picture. For Testing, it is Raised Inside the Cold Shroud.

Representative results for an operational ESR test sample are shown in Figures 6a and b. These samples were fabricated using the ST5 footprint described previously; however, non-flight grade materials and processes were used in the fabrication of the radiator film. These graphs show the power required to maintain the substrate temperature as the high voltage is alternately applied to the film. The ESR in Figure 6a was constructed from a membrane consisting of 0.0005" thick polyimide film with an aluminum coating (Dunmore Corp) and overcoated with a commercial black paint. This shows the power switching from 4 to 5.5 W. The switched area is 57.6 cm^2, and corresponds to a change in radiated power of 26.0 mW/cm^2 (uncorrected). Figure 6b shows results on a slightly thinner polyimide membrane. This is a 0.0003" thick polyimide with an aluminum coating, again coated with a commercial black paint. In both of these samples, the applied voltage was switched between 300 VDC and zero. This sample shows initial switching from 4 to 5.2 W; however, the performance of this film improves with cycling, eventually reaching an "on" state power of 5.45 W.



(a.)



(b.)

FIGURE 6. (a.)ESR thermal vacuum test results. Membrane is 0.5 mil aluminized polyimide film with commercial black paint. (b.) ESR thermal vacuum test results. Membrane is 0.3 mil aluminized polyimide film with commercial black paint.

This effect is repeatable. Figure 7 plots the radiated power versus the number of applied cycles, showing the increase in the "on" power. This effect is thought to be a result of the membrane relaxing as it reaches the higher substrate temperature. The application of a small number of cycles, of short duration at each switching from "off" to "on" has been adopted as a standard voltage application technique and is referred to as "pre-triggering". This pre-triggering consists of 10 pulses of 3 second duration applied each time the sample is switched "on". Results for a sample with pre-triggering are shown in Figure 8. This figure shows results obtained for an ESR fabricated with a flight grade conductive black paint, Aeroglaze Z307, applied by NASA at the Goddard Space Flight Center. This paint is somewhat thicker than the commercial paint used in the previous measurements. It is applied over an aluminum layer and includes a primer. This sample was found to switch ~ 1.4 watts, for a radiated power change of 24.3 mW/cm^2.

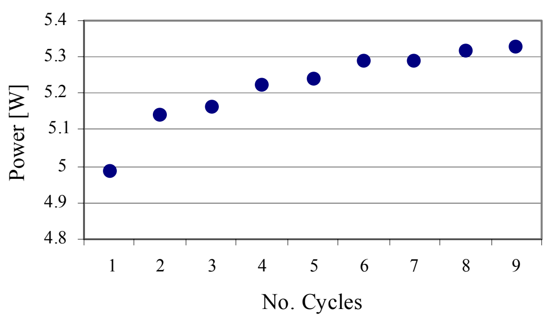


FIGURE 7. Radiated Power Versus Number Of Applied Voltage Cycles.

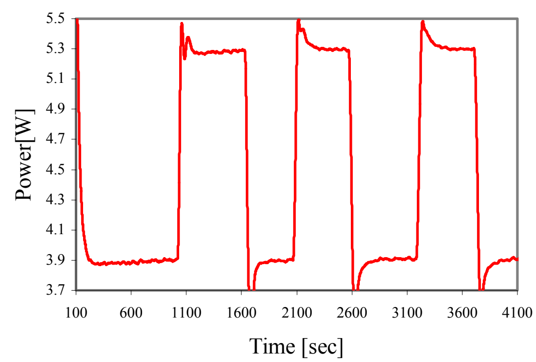


FIGURE 8: ESR Thermal Vacuum Test Results, 0.3 mil Aluminized Polyimide Film with Aeroglaze Z307 paint, Using Pretriggering on Each Voltage Application.

FLEXIBLE APPLIQUÉ

To reduce the operating voltage and permit easier application, it is envisioned that the next generation ESR will be fabricated as an appliqué which can simply be attached to the outer skin of the spacecraft. Since the heat flows are small, it is relatively easy to have this ESR appliqué be electrically isolated but in good thermal contact with the skin. The present ST-5 configured ESR design has a number of similarities to an appliqué. The unit is being fabricated on a thin (.010") printed circuit board with the membrane directly attached to this secondary substrate, which is then adhesively bonded to the primary substrate. However, the primary purpose of the appliqué will be to achieve operation at significantly lower voltages. We currently are pursing this approach with preliminary proof of concept research indicating its feasibility. However, detailed design, sample fabrication and testing only recently has commenced. The following discusses this preliminary process. This approach uses a sacrificial layer (copper) and a photosensitive polyimide. The polyimide is applied and patterned on a metal substrate (copper). The copper is then selectively etched to leave the support structure. Although not yet a production process, the following process has produced virtually complete micro-ESR's. The fabrication process is as follows:

1) Starting substrate – ½ oz. copper foil (this also gives the height of the stand-off).
2) Spin coat the entire substrate with polyimide, dry and bake.
3) Spin coat the entire substrate with photoresist, dry and soft bake.
4) Expose the front side with a pattern which defines the polyimide.
5) Develop and etch pattern.
6) Hard Bake (this forms the polyimide).
7) Laminate (use strippable adhesive, e.g. cyanoacrylate) to support the substrate.
8) Pattern the back side of the copper to defines stand-offs.
9) Develop and etch copper.
10) Attach to final (patterned) base and release from hard substrate.
11) Sputter ITO layer onto polyimide.

All parts of the above process were demonstrated by fabricating samples. These consisted of individual membranes, measuring 5 mm x 5 mm in size.

Since it will be necessary to characterize individual device performance, a redesign of our measurement system is underway to use direct imaging with an externally mounted IR camera. Although lacking the accuracy of the present calorimetric test system, it will permit direct measurement of the performance on small elements; a necessity to identify losses in the structure. These test system modifications and fabrication of testable devices are expected to be complete during the first quarter of 2004.

CONCLUSIONS

In this paper we have described some experimental results on an existing thermal control device which uses electrostatic hold-down of a high emissivity composite film to control spacecraft skin temperature. Results were presented on the changes in radiated energy as measured in a vacuum with a LN2 background and related to changes in apparent emissivity values. We also have described an effect in which the performance can be improved by "pre-triggering" the sample with a number of pulses. Finally, we have discussed the preliminary approach to develop the device as an appliqué which can be applied directly to the spacecraft skin.

NOMENCLATURE

ε = emissivity
$\Delta\varepsilon$ = change in emissivity between operational states
C_{vs} = ESR substrate heat capacity (J/K)
H_{in} = thermal vacuum system heater input power (W)
H_{leak} = thermal vacuum system leakage (W)
M_s = ESR substrate mass (kg)
P = thermal vacuum system test pressure (torr)
P = power (W)
R_{back} = thermal vacuum system radiation from ESR to backplane (W)
R_{cold} = thermal vacuum system radiation from shroud to ESR (W)
R_{hot} = thermal vacuum system radiation from backplane to ESR (W)
R_{rad} = thermal vacuum system radiation from ESR to shroud (W)
t = time (s)
T = temperature (K, °C)
T_{low} = thermal vacuum system shroud temperature (K, °C)
T_{ref} = thermal vacuum system backplane reference temperature (K, °C)
T_s = ESR substrate temperature (K, °C)

ACKNOWLEDGMENTS

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